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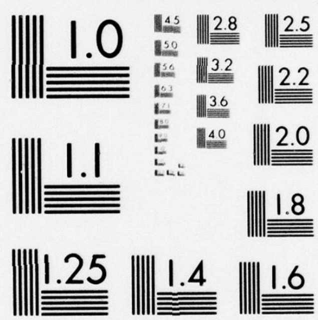

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Aspects of a Theory of Simplification, Debugging, and Coaching

Gerhard Fischer, John Seely Brown, and Richard R. Burton

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ABSTRACT

Today, millions of people are learning to ski in just a few days instead of the months it took to learn twenty years ago. In this paper, we analyze the new methods of teaching skiing in terms of a computational paradigm for learning called increasingly complex microworlds (ICM). Examining the factors that underly the dramatic enhancement of the learning of skiing led us to focus on the processes of simplification, debugging, and coaching. We study these three processes in detail, showing how the structure of each is affected by the basic skills required to perform a task, the equipment involved in its execution, and the environment in which the skill is executed. Throughout, we draw parallels between the process of learning to ski and learning computer programming and problem-solving.

Our goal is to achieve insight into the complex issues of skill acquisition and design of learning environments -- especially computer-based ones -- through the analysis of the intuitively understandable domain of ski instruction.

1. INTRODUCTION

The most effective use of computers for education is to support active learning environments in domains that previously had to be learned statically. While some work, though not nearly enough, has gone into developing particular environments, much less has gone into clarifying the general issues that affect the acquisition of a skill in a complex environment.(1) Our own work has led us to believe that a thorough analysis of skill acquisition is necessary to augment our intuitive understanding of the subtleties involved in designing the next generation of learning environments.

In this paper, we examine the learning of an extremely complex skill, skiing, through the language of computational learning environments. We have two goals. One is to explicate the remarkable advances in the methods of teaching skiing, which have greatly reduced the time required to learn to ski. The other is to analyze the features of the highly successful skiing learning environment in an attempt to articulate the fine grain structure of a theory of learning environments and to identify principles to guide the design of computer based learning environments.

(1) Although one would expect research in the fields of task analysis and behavioral objectives to be relevant, it has not been. This is in part due to the lack of a precise computational theory of teaching and learning, and in part to the lack of appropriate

The paradigm on which we shall base our examination of the teaching of skiing is called "increasingly complex microworlds" (ICM). In this paradigm, the student is taken through a sequence of environments (microworlds) in which his tasks become increasingly complex. In the analysis of skiing, the aspects of the ICM paradigm we will stress are simplification, debugging, and coaching. Throughout the discussion, we will also point out how the learning experience (as viewed from the ICM paradigm) has been implemented in skiing by three fundamental components of the learning experience: the basic skills required to perform a task, the equipment involved in its execution, and the environment in which the skill is executed. The analysis of skiing raises a host of general questions that should be asked when designing learning environments based on the ICM paradigm. For example, which kinds of simplification can stand in isolation, and which require explicit coaching to prevent the induction by the student of false models that later must be unlearned? Throughout our analysis, we shall draw parallels to skiing from the domain of learning environments that teach computer programming and problem-solving.

2. <u>Why Skiing</u>?

Skiing is an extremely complex skill, to learn and to perform. It is representative of an important class of real-time control skills (or data driven skills), where error correction is essential in order to cope with deviations and sudden changes in the expected

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languages for discussing the deep structure knowledge representation of a domain.

environment. However, highly successful methods have been developed to teach skiing. This is not true for most other complex skills. These methods suggest criteria necessary to design successful learning environments for other complex skills. In addition, skiing provides an intuitively understandable domain, with which many people have personal experience.(2) Even nonskiers can relate the examples used in learning to ski to other physical skills, such as bike-riding.

2.1 Skiing as a Success Model

Skiing is an instance of a success model (Papert 1976); it is an example of the successful acquisition of a complex skill. In skiing, the conditions of learning are more important than the total time or mere quantity of exposure. This implies that the teaching of skiing has evolved into a highly successful instructional process. The two main uses of a success model are:

1. to identify the features that make it successful
2. to abstract these features and try to transfer them to less successful learning situations.

We do not have a complete theory to explain why the learning process in skiing was so dramatically enhanced during the last twenty years, but we are convinced that the following features were of great importance:

(2) Our knowledge and insights about skiing are drawn primarily from one of the authors (Fischer) who has worked as a part-time ski instructor for many years.

- Redefinition of teaching goals
- Improved equipment
- Access to new environments
- Better teaching methodologies and conceptualizations.

We are aware that other factors influence the learning process besides the ones we investigate in the following sections. All ski areas have many expert skiers around, so that learning can take place according to the medieval craftsman model. This enhances the ability of the less experienced skier through interaction with the more experienced one.

The person learning to ski is highly motivated. Skiing is fun. It provides a wide variety of experiences; every run is different from the previous run. Skiing is good exercise. It provides a nice change in the life style of many people. In addition, societal pressures contribute to the motivation to learn to ski. Being a skier is fashionable. We will ignore the problems of motivation in this discussion and will assume that the learner is motivated. Although motivation is clearly an important consideration in the design of learning environments, we shall not address it in this paper.

We must also note a few of the negative aspects of skiing: it is expensive, it is time-consuming, and it can be dangerous. For these reasons, the task of identifying the aspects of skiing that make it a success model becomes even more interesting.

2.3 The ICM (Increasingly Complex Microworlds) Paradigm Applied to Skiing

The acquisition of a complex skill is difficult when the starting state and the final state are too far apart. Good learning environments, structured according to the ICM paradigm, provide steppingstones or intermediate levels of expertise so that within each level the student can see a challenging but attainable goal. In skiing, technological advances and the methodologies built around these advances make it easy to get started. This means that practice (a task within an intermediate level) is not considered a form of torture that must be endured before the learner can enjoy excellence.

As an example of the ICM paradigm in skiing, consider a novice learning to ski. The student begins on short skis over smooth terrain. The short skis allow him to develop rhythm, and they make it easier to turn and get up from a fall. The smooth terrain limits his speed and reduces the danger. As the student gains ability within these constraints, he is given slightly longer skis and steeper, more complex slopes until he is using full length skis on uncontrolled slopes. At each step, the microworld in which he must perform is made increasingly complex.

We should point out that the ICM paradigm may be usefully applied to sports other than skiing. A large body of knowledge about skill acquisition is available in the literature of different sports. The authors of textbooks for these sports supply a great deal of knowledge about the critical components and essential

steppingstones for the complex skills they describe, as well as awareness of the most common problems and special exercises to eliminate them. However, these authors often lack a conceptual framework that would allow them to generalize their knowledge or to structure it according to different criteria.

We would like to acknowledge the work by Austin (1974). He analyzed the skill of juggling in terms of a computational metaphor and used the resulting analysis to develop novel methods of teaching juggling. In our work, we seek to analyze the process of learning to ski within the framework of the ICM paradigm, with the goal of expanding the paradigm.

3. Aspects of a Theory of Simplification

One of the major design decisions within the ICM paradigm is choosing or generating appropriate microworlds. The primary means of generating alternative microworlds is through simplification. This section describes a taxonomy of knowledge, methods, and heuristics that could serve as a basis for evolving a theory of simplification in the learning process.

Simplifications are possible in each of the three major components of the learning process: the skill required to perform a simplified version of a task, the equipment involved in executing the task, and the environment in which the task is executed. Often it is not just one of the components, but their synergistic interaction, that leads to powerful learning microworlds.

3.1 The Basic Skills

The designer of a learning environment can select some beginning microworlds for developing particular subskills in isolation. Some of the basic physical skills of skiing can be taught without skiing. Students can thus develop these subskills without having to deal with the interactions and side effects of the whole aggregate of subskills. Examples would be: learning a certain rhythm, strengthening certain muscles, and improving the mobility of certain parts of the body. At a more advanced level, a trick skier may practice his somersaults into a pool or on a trampoline.

Great care must be taken to choose a microworld in which the simplified skill is isomorphic in its most important components to the final form of the skill (see Section 3.5). In juggling, the skill of ball-handling can be practiced with one or two balls. This develops the necessary subskills of tossing and catching, as well as hand-eye coordination. However, the easiest form of three-ball juggling, called cascade juggling, can't be simplified to an isomorphic two ball juggling (see Austin, 1974).

3.2 The Equipment

The best known example of a simplification of equipment in skiing is the graduated length method. In this method, a beginner skier is started on short skis. As the student becomes proficient, his skis are gradually lengthened to (whatever may be considered) full length skis. Short skis are used as transitional objects in

the learning process. They make it easier to get started and make early success more likely. At the next level, the shorter skis are not needed anymore. An interesting perspective on the hand-held electronic calculator may be to view it as a transitional object in learning mathematics. Similarly, the computer may serve as a transitional object in learning how to build cognitive models.

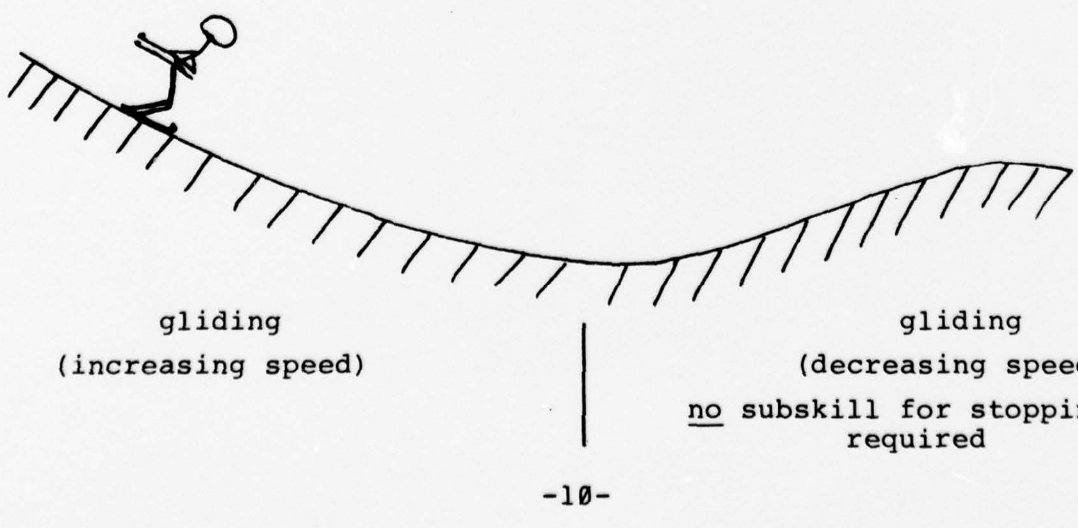
It is interesting to ask why it took so long for someone to think of using short skis in the learning process. For one thing, skiing itself changed. Twenty years ago, people wanted to ski fast in straight lines for which longer skis are better. Nowadays the final state of expert skiing involves making many turns (which is facilitated by short skis). For another thing, teaching by the graduated length method requires a different instructional organization. To be economically feasible, the new method needs large ski schools where students can rent short skis instead of buying them, so they can be returned after they are no longer needed. The economic consideration that has hindered exploration of transitional objects in learning will not be as important in computer-based learning environments, because the transitional objects are symbolic structures.

Short skis are not the only technological improvement in the equipment used in skiing. Safety bindings reduce the fear and eliminate the catastrophic consequences of wrong behavior, therefore, supporting an active approach to mastering new challenges. (In an interactive computer system, the "UNDO" command supports a similar type of exploration because it reduces the risk

involved in making errors.) Ski tows and gondolas provide access to new environments in the form of moderately steep and wide glaciers with snow conditions suited to the early phases of the learning process. In addition, they increase considerably the time that people can actually spend skiing. A parallel improvement in computer programming is the development of time-sharing systems and languages that reduce the amount of time a student spends waiting for his program to be run.

3.3 The Environment

Skiing (as we have pointed out before) is an aggregate of subskills. A major aid in learning any complex collection of skills is the opportunity to practice the subskills independently. We must design or find microworlds structured to allow a learner to exercise particular skills. For the beginner in skiing, gliding and stopping are two essential subskills that have to be learned. But stopping cannot be practiced without gliding, and gliding is dangerous unless you know how to stop (in Simon's words (1969), the system is only nearly decomposable). The problem can be solved by choosing the right environment:



This example leads us to state: <u>The decomposability of a skill is a function of the structure of the environment as well as of the skill itself</u>.

Modern ski areas have made another important contribution to the simplification of the environment. They provide the novice with constant snow conditions. A beginner can first learn to maneuver well on packed slopes without having to worry about the variabilities of ice or deep powder. In learning to play tennis, the ball shooting machine provides a similar form of simplification. Having a supply of nearly constant balls removes some of the variables from the process of learning a stroke.

The wide variety of slopes in a large ski area has another important impact on learning. It allows the coach to choose a microworld dynamically according to the needs of the learner; this eliminates the need to force every learner through the same sequence of microworlds.

3.4 Simplification's Dependency on Top-level Goals

Technological improvements have eliminated certain prerequisites for skiing, that is, they have simplified skiing by <u>removing inessential parts</u>. It is not necessary any more to spend a whole day of hard physical exercise in order to gain a thousand meters of elevation to ski one nice run. The goal of skiing is gliding downhill successfully, not getting stronger muscles and a better physical condition by climbing uphill for several hours. If climbing were one of our top level goals, the use of gondolas and

chair lifts would hardly be an appropriate simplification towards the acquisition of these skills. Clarifying the top level goals may imply a different standard of measurement for the hierarchical ordering of the subskills and a corresponding change in the sequence of microworlds.

The importance of clarifying top-level goals can also be seen in programming. As computing becomes cheaper, concerns about machine efficiency will be replaced by concerns about cognitive efficiency, how to facilitate the understanding and writing of programs. This change in perspective requires new conceptualizations and methodologies, which will lead to a new set of simplifications for the acquisition of the skills of programming and problem solving (Fischer 1977).

3.5 Useful Versus Possible Simplification

The range of possible simplifications is much larger than the range of useful simplifications. The designer of a learning environment must look carefully at what each microworld does for the overall goal. Several possible uses for a microworld come to mind. A microworld:

- Makes it easier to begin learning a skill by creating the right entry points
- Accelerates the acquisition of a skill
- Provides intermediate goals/challenges that are (and seem to be) attainable

- o Provides practice of the important subskills in isolation, allowing the common bugs to occur one at a time instead of in bunches

A complicating factor in choosing microworlds is that <u>non-monotone</u> relationships often exist between simplifications of the microworld and the corresponding simplifications of the task. Using a moderately steep hill to practice is a useful simplification for the following reasons:

- o Is easier to control speed.
- o The student doesn't have to make big turns and can stay closer to the fall-line.
- o The student doesn't have to lean away from the hill with his upper body (which appears to be counterintuitive for many people and increases their fear).

The interesting fact is that this is not a monotone relationship: If the hill is too flat, it may be impossible to attain enough speed to turn. Another example of this sort is that skiing is difficult on a slope with big mogels, but, in making turns, small mogels can be very helpful.

3.6 <u>The Danger of Oversimplification</u>

Skiing is representative of an important class of real-time, data-driven control skills. This means that a sudden, unexpected change in the environment requires high-order error correcting and debugging skills to cope with the deviations. If the microworlds are too friendly (which may serve well in getting started) they may

suppress the development of these higher-order skills. The skier must learn to cope with icy spots and rocks that lie hidden under soft snow.

Developed ski areas themselves constitute a simplification, because they close avalanche areas and keep the skier away from cravasses, they pack down slopes, they rescue people if they get hurt, etc. This implies that people skiing only in these areas never acquire the planning and debugging knowledge they need to move around in more hostile environments. One danger of working with simplifications is that they may lead to unjustified extrapolations. One task of a good coach is to reduce the level of protectiveness gradually (not all ski areas eliminate the need for stopping) and lead people to the right new challenges. There is another danger: Learning to perfect the performance in one environment, such as packed slopes, may reduce the willingness of a skier to practice in powder, because the difference in his performance between the two environments may be too great.

Both of these dangers can be seen in efforts to teach computer programming that start with BASIC. The linear nature of a program in BASIC and the small size of solutions to typical introductory problems often lead students to develop debugging strategies that will not generalize to large programs. One such strategy is to step through a program one statement at a time. Some students also resist leaving friendly (albeit limited) BASIC environments, in which they can adequately solve small problems, for the complexities of data declarations, functional decomposition, and advanced control

structure statements. Note that these extrapolations are not ones intended by those who have designed the learning environment. They arise from simplifications made to create the microworlds in BASIC. Understanding the inappropriate generalizations that can develop in each microworld is one of the tasks facing a learning environment designer.

4. DEBUGGING

4.1 The Importance of Debugging to the ICM Approach

As a student moves from one microworld to one at next level of complexity, he may need to modify his knowledge in several ways:

- New subskills may be introduced that must be mastered (skiing over mogels).
- Changes in the environment may require new interactions between skills (gliding and stopping).
- Some skills that were idiosyncratic to a microworld may have to be unlearned.

While a designer should strive for simplifications that reduce the chances for incorrect generalizations, this is not always possible nor necessarily desirable. In skiing, an instructor has the problem of how to deal with the poles. Even though they are quite important for the advanced skier, the only major skill a beginner need learn is to carry them so that he won't hurt himself. While practice without poles would prevent formation of any inappropriate skills, empirical evidence suggests that eliminating the use of poles is not a useful simplification. Even if they are

used incorrectly, the poles still support balance and mobility, and it is apparently easier to unlearn an incorrect use of poles than to incorporate the poles into a learned skill without using them from the beginning. The goal of a sequence of microworlds is not to remove all chances for misconceptions, but instead to increase the possibility that the student will learn to recognize and correct his own mistakes.

4.2 Nonconstructive Versus Constructive Bugs - Implications for a Piagetian Environment

An important characteristic of a Piagetian environment (Papert, 1978) is the notion of a constructive bug: the learner gets enough feedback to recognize a bug, to determine its underlying causes, and on this basis, to learn procedures to correct the bug. This notion is sharply contrasted with the notion of a "nonconstructive" bug, where a student may recognize he is wrong but not have the necessary information to understand why.

The critical design criterion for selecting the right microworld may well be finding an intermediate microworld that transforms nonconstructive bugs into constructive ones. From the domain of skiing, examples of environmental support for such a transformation follow:

- If the skier leans too much to the hill with his upper body, a change to a steeper hill will indicate this to him, because he will start sliding down the hill.

- If he holds his knees too stiffly, trying to stay on the ground while skiing over a bumpy slope will point out his inflexibility.
- If he doesn't ski enough on the edges of his skis or if he makes turns too sharply, a slope with soft snow, where he can observe his tracks, will indicate where each of these conditions are occurring.

In all of these cases, the microworld is chosen to allow the student's previous experience to be used to debug the new task.

A good coach knows a large number of specific exercises (micro-microworlds) designed to transform nonconstructive bugs into constructive ones. These exercises are goal-directed toward certain bugs. His expertise must include the ability to distinguish the underlying causes (which may be hidden and indirect) from the surface manifestations of the bugs. To mention just one example: lifting up the end of the inside ski in a turn provides the skier with the feedback that most of his weight is on the outside ski (where it should be). Exercises of this sort (which provide the basis for self-checking methods) are of vital interest and are essential in teaching and learning a physical skill (for examples, see Carlo, 1974 and DVSL, 1977) whereas in the cognitive sciences, research in self-checking methods is still in its infancy (see Brown and Burton, 1978).

Another way to turn nonconstructive bugs into constructive ones is through the appropriate use of technology. The most obvious example is the use of a video camera, which helps the student to compare what he was doing to what he <u>thought</u> he was doing.

5. Coaching

Acquiring a complex skill, even when supported by a good learning environment and appropriate technology, does not eliminate the need for a good coach. The introduction of simplifications increases the importance of a coach. He must be able:

- o To make sure that within each microworld the right subskills are acquired, instead of ones that would later have to be unlearned.
- o To design the right exercises, provide the right technology, and select the right microworlds to turn nonconstructive bugs into constructive ones.
- o To perform a task in the student's way in order to maximize the student's chances of recognizing his bugs.
- o To mimic and exaggerate the behavior of the students.
- o to explicate his knowledge in terms the student can understand and execute.

The following example may be used to illustrate the need for executable advice. Many books are written from the instructor's point of view. The student often receives advice (in the book or on the ski slope) that he cannot execute. An example of such advice is, "Put your weight forward," given to skiers who don't know where their weight is. The instructor tells the student the "what" without telling him the "how" and without providing him with knowledge or procedures to translate the "what" into the "how".

Let us give another example of the distinction between executable and observable advice. When skiing in powder snow, the advice, "Your ski tips should look out of the snow", is <u>observable</u> by the student. That is, the student can see whether his ski tips stick out of the snow or whether they are buried below the surface. But the advice is not directly executable. The corresponding executable advice would be "Lean backward," (or "Put your weight backward", if he knows how to shift his weight. This advice is not directly observable. The interesting dependency relationship is that the "what" can be used to control the "how." The change in language from "how" to "what" as a process becomes understood, characterizes the movement from machine to higher-level programming languages.

Let us mention briefly a few other important aspects of coaching. The coach must:

- o Draw the borderline between free and guided exploration (free exploration in a dangerous environment could end up with the student in a cravasse or an avalanche)
- o Decide when to move on to avoid simplified versions of the skill that cause bad habits
- o Be aware that coaching is more important at the beginning of the acquisition phase then later on because a conceptual model must be created, entry points must be provided, and self-checking methods must be learned (to overcome the problem that it is hard to give yourself advice).

6. Aspects of a Theory

There is no doubt that a theory of simplification, debugging, and coaching would provide us with better insight into the complex issues of skill acquisition and design of learning environments. We hope that our observations, examples, and conclusions are a first step toward this end. We believe that a theory of this kind will not be reducible to one or two general laws; that is, we won't be able to characterize such a theory with a few theorems. We expect that the difficulties encountered in constructing a crisp theory in the domain of learning environments will be similar to those encountered, for example, in developing a theory of semantic complexity, (Simon, 1969).

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